Probing Quantum Gravity with exceptional VHE flare from the Active Galaxy PKS2155-304

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Challenges in Particle Astrophysics, Blois 2008

Lorentz Invariance and Quantum Gravity

Quantum Mechanics & Special Relativity & General Relativity
(fundamental constants h, c, G_N, define units of length, mass and time)
waiting for unique theory of (space, time)

$\rightarrow$ Quantum Gravity still under construction

Quantum Gravity effects on tiny Planck scale ≈ 1.6 10^{-33} cm
or at $E_P \approx 1.2\ 10^{19}$ GeV

Imprint at Energy < E_P if gravity violates some fundamental symmetry of the effective low energy theory: Lorentz Symmetry

"Three roads to Quantum Gravity" (Lee Smolin, 2000):

- in Loop Quantum Gravity scheme
  (e.g. Gambini, Pullin 1999, Alfaro et al., 2002)
- in extra-dimension String Theories
  Liouville strings, space-time foam, non-comutative geometry, …
  (e.g. J. Ellis, N. E. Mavromatos, D.V.Nanopoulos 1999, L.J. Garay 1998, G. Amelino-Camelia 2001,)
  leading to Lorentz Symmetry breaking
- Black Hole thermodynamics – physics at Planck scale

Quantum Gravity: space-time foam

Space-time foam: modification of the propagation of energetic Particles due to nontrivial refractive index n(E) induced by Quantum Gravity fluctuations in the vacuum

$\rightarrow$ distortion of the standard dispersion relations ($E \ll E_P$)

$$E^2 = p^2(1 + \xi\,(p/E_P) + \zeta\,(p/E_P)^2 + \dots)$$

Linear deviation

$$\xi < 0: \quad v = c(1 - E/E_{QG}),\ n(E) = 1 + E/E_{QG}$$

Quadratic deviation

$$\xi = 0,\ \zeta < 0: \quad v = c(1 - E^2/E^2_{QG}),\ n(E) = 1 + E^2/E^2_{QG}$$

We expect: Lorentz Symmetry violation and $E_{QG} < E_P$

Quantum Gravity effects from distant sources

- G. Amelino-Camelia, *(see e.g. Perspectives on QG, 2003)* first proposed variable astrophysical sources to probe for Lorentz Invariance breaking and for Quantum Gravity scale measurements – GRBs and Blazars (and Pulsars)

- The modification of the group velocity would affect the simultaneity of the arrival times of photons with different energies): $c(E) = c_0\,(1 \pm f\,(E/E_P))$

- Light propagation from distant Astrophysical Sources is affected by the expansion of the Universe

$$\Delta t = \mathrm{H}_0^{-1} \frac{\Delta E}{\mathrm{E}_{\mathrm{QG}}} \int_0^z \frac{(1+z)\,dz}{h(z)}$$

$$h(z) = \sqrt{\Omega_\Lambda + \Omega_\mathrm{M}(1+z)^3}$$

In the Newtonian approximation (analysis of PKS2155-304 flare):

linear term: $\Delta t = \xi\, L/c\, \Delta E/E_{QG}$

(L distance of the source, ΔE energy range, E_{QG} scale
$\xi = \pm 1$ or ξ measured/constraint if $E_{QG} = E_P$)

PKS2155-304 VHE flare data

Observations by H.E.S.S. *(see Werner Hofmann's talk)*
on 28/07/2006 during ~ 1.5 hr

Active galaxy PKS2155-304 is a brightest blazar in Southern Hemisphere observed in all wave-lengths (Radio -> VHE)

High redshift, z = 0.116, of PKS2155-304 opens
a new redshift domain for population studies of time-lags from AGNs

Electromagnetic boosted emission in jets towards the observer with Doppler factor of ~ 100 (this flare) → constraints on the emission

Jets powered by accretion/ejection onto a SMBH of 10^9 M_{sol}

Flare on MJD53944: highest intensity and variability ever observed

PKS2155-304 VHE flare data

Standard H.E.S.S. analysis (*cf. Aharonian et al., A & A 457,899 (2006)*)

Statistics after cuts ~ 10000 photons for analysis

Flux (I > 200 GeV) = 1.72 10^{-9} $cm^{-2}s^{-1}$ (7 x CRAB flux)

Energy spectrum: broken power-law
No strong indication of spectral variability

Light Curve presents several well resolved bursts well described by Norris function (fast rise, slow decay) similar to GRBs

Fourrier power spectrum analysis shows variability < 600 s

<u>Goal of this study:</u>
Search for time-delays between Light Curves of different energies to quantify a possible energy dispersion with 2 methods

Time lags: methods for deriving E_{QG}

- Cross Correlation Function (MCCF) – GRBs (BATSE)
  HESS: PKS2155-304

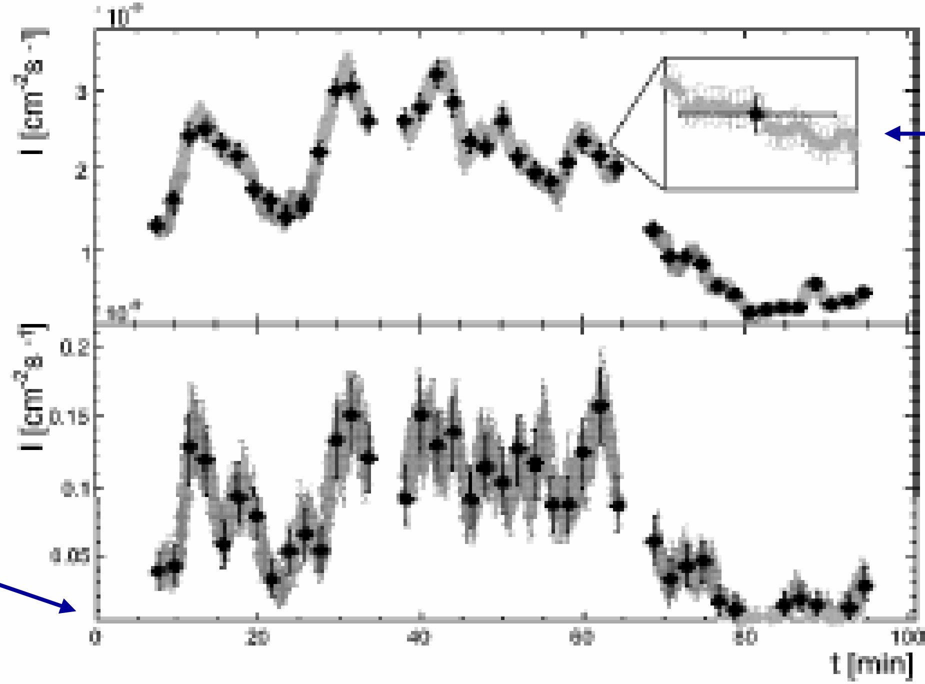
- Energy Cost Function (ECF) – GRBs (?)
  MAGIC: Mrk501

- Wavelet Transforms (CWT) – GRBs (BATSE, HETE2, SWIFT)
  HESS: PKS2155-304

- Likelihood fit of E_{QG}/E_{Planck} – GRBs (INTEGRAL)
  MAGIC: Mrk501

For robust results:
- use of at least of 2 methods (different aspects of the Light Curve)
- need of error calibration by Light Curve simulations

Light curves



zoom ~62 min

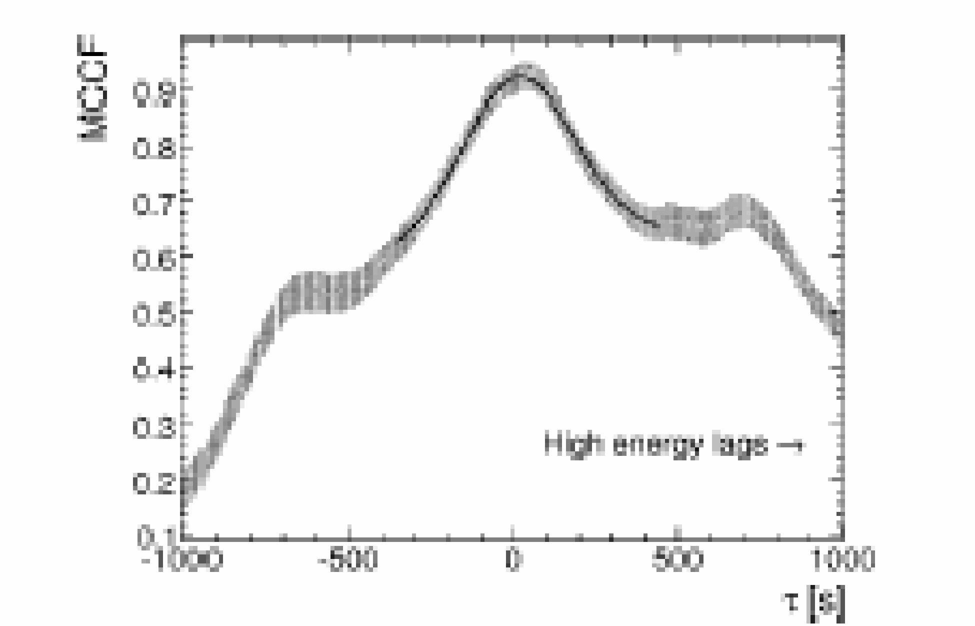
MJD 53944.02

Energy ranges 0.2-0.8 TeV, > 0.8 TeV
(CWT uses 0.21 – 0.25 TeV, > 0.65 TeV)

Light Curves over sampled by a factor of 24
(neighboring flux bins shifted by 5 s with respect to each other)

Observed: Fast variability ~100 s – bursts in in the Light Curve

MCCF measurement



Cross-correlation function: *(T.-P. Li, at al., 2004)*

$$\mathbf{MCCF}(\tau, v_1, v_2) = \frac{\sum_{i=\mathrm{Max}(1,1-k)}^{\mathrm{Min}(N,N-k)} v_{1i} v_{2(i+k)}}{N\sqrt{\sigma'_{v1}\sigma'_{v2}}}$$

applied to over sampled light-curves

Fit: gaussian + a const

→ the central peak distribution at <u>20 s</u>

error determined by a calibration procedure

CWT measurement

- Peak-finding procedure applied to 2 Light Curves with different energies, similar to method for GRBs *(J. Ellis, et al., 2003)*

- Continuous Wavelet Transform (e. g. Mexican Hat) of the Light Curve characterizes its variation over a given scale at a given time

- Singularities (maxima and minima) are characterized by a Lipschitz coefficient *(Mallat,1999)* found with LastWave package *(Bacry, 2004)*

- 2 steps: - measurement of extrema position
  - pair association between 2 Light Curves
    same or adjacent bins
    conditions on Lipschitz coefficient and its error

2 – 5 pairs found depending on "energy gap"
(final choice of $\Delta(E_1^{mean} - E_2^{mean}) = 0.92$ TeV)

MC simulations

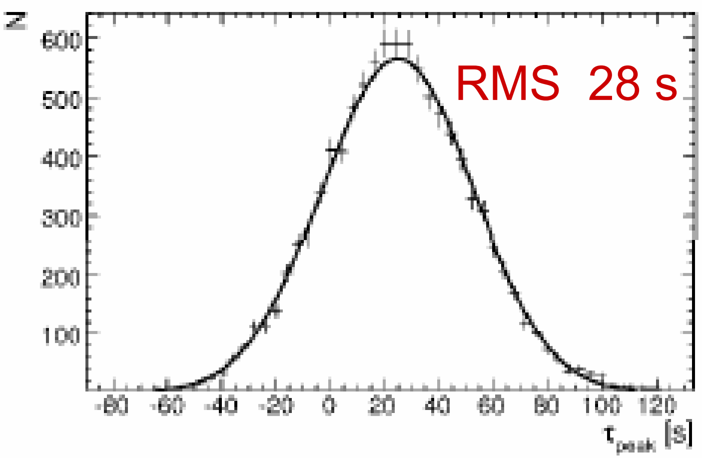
1. producing modified Light Curves within experimental errors, allowing fluctuations at the level of the finest time bin (5 s)
   → for linear shift in energy 10000 simulations with artificially introduced time-lag (-90 to 90 s TeV^{-1}, steps 15 s)

2. photon lists generated with parametric bootstrap according to smoothed version of the Light Curve and experimental spectrum
   → 1000 photons for each MC (1.) dispersion condition

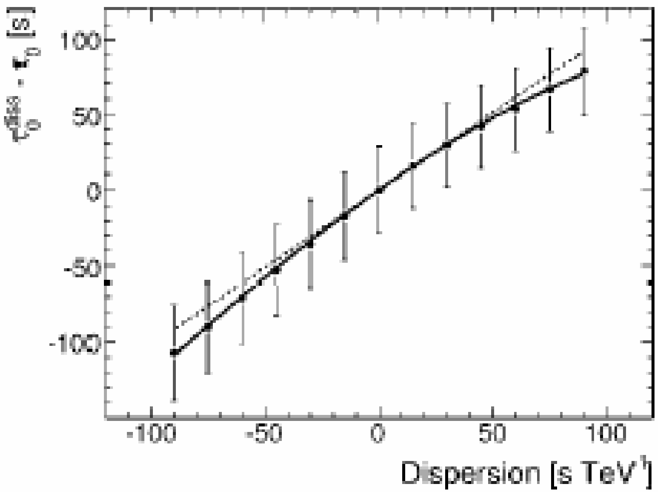
3. accidental association in pairs (CWT) was estimated with simulated LC randomly produced spikes or bumps assuming mean flux, variability spectral index and the flux variance, on a long time scale

   → probability of stochastic associations < 0.1%

MCCF: error calibration



10000 simulations MC (1.)



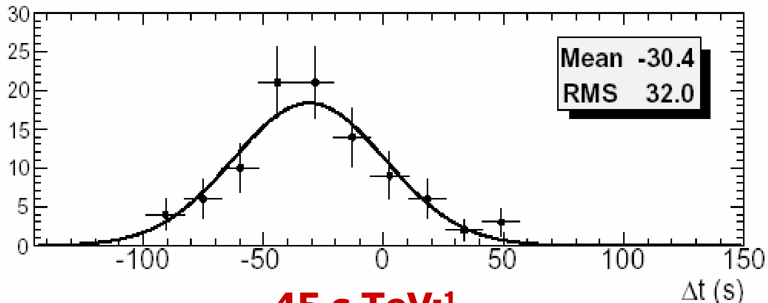
For each pair of Light Curves:

peak (τ) of MCCF was found
→ Cross-Correlation Peak Distribution (CCPD)

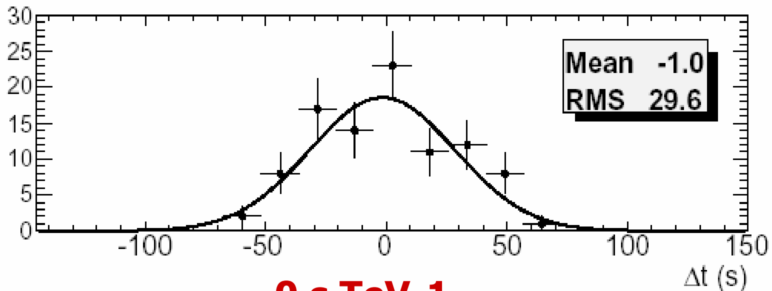
Error calibration curve as function of energy dispersion introduced in H.E.E.S. data:

best fit: 3rd order polynomial

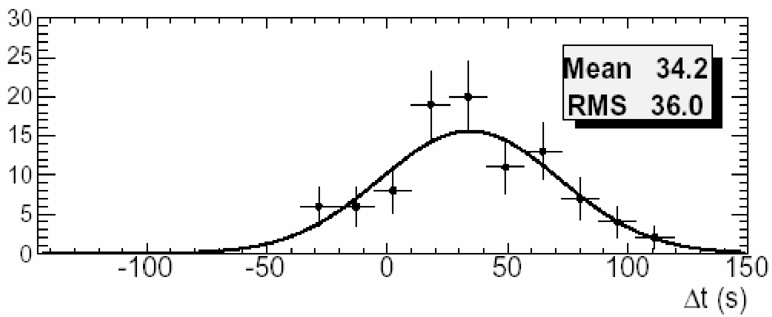
CWT: error calibration



-45 s TeV^{-1}



0 s TeV-1



45 s TeV^{-1}

3 points of error calibration curve
with different smearing
each point:
100 samples of simulated data
with bootstrap MC (2.)

Mean no of pairs: 2.9

→ error on Δt:
30 -35 s (10% precision)

→ ~10 s systematic shift in mean

Results: time-lags and errors

Method	ΔE (TeV)	Δt (s)	Error (s)	$\Delta t_{95\%\ CL}$ (s/TeV)
MCCF	1.02	20	28	73
CWT (2 pairs)	0.92	27	30	100

Systematic errors checked:
- selections of photon sample and energy determination
- other binning and over sampling factors
- choice of energy domains
- CWT: impact of cuts for extrema identification and pair association

Considered as negligible with respect to a 30 s statistical error

Constraints on ξ, ζ and QG energy scale

Method	ΔE (TeV)	$\xi_{95\%\ CL}$	$E_{QG\ 95\%\ CL}$ (10^{17} GeV)	$\zeta_{95\%\ CL}$	$E_{QG\ 95\%\ CL}$ (10^{9} GeV)
MCCF	1.02	< 17.6	> 6.9	$< 1.2\ 10^{9}$	> 1.0
CWT	0.92	< 24.2	> 5.0	$< 1.7\ 10^{9}$	> 1.5

- The difference between 2 methods:
  energy gap and larger Δt measured with CWT
- Best limits on:
  dispersion relation parameters ξ, ζ and QG energy scale
- Low sensitivity to the quadratic term

- Results not compatible with interpretation of Mrk501 (MAGIC) flare time-lag in terms of Quantum Gravity

Summary

- Analysis of the Exceptional Flare of PKS2155-304 in 2006 with H.E.S.S. allows to study Fundamental Physics from Astrophysical sources with unprecedented precision

- No significant time-lag detected in PKS2155-304 data (> 3σ) for minute time scales and $\Delta E \sim 1$ TeV with MCCF and CWT methods

- Highest values for Quantum Gravity scale found with Blazars:

  under <u>assumption of no source effect</u>

  QG scale > 0.7 10^{18} at 95% CL
  linear parameter $\xi = M_P / E_{QG} < 17.6$

- Various redshift studies are needed to distinguish between source effects and Lorentz Invariance breaking
  future population studies – GLAST (GRBs), CTA (Blazars)

Studies with GRBs

- With GRB 021206
  - S. Boggs *et al.*, ApJ 611 (2004) L77
  - $E_{QG} > 1.8 \times 10^{17}$ GeV
- With 9 GRBs with known z seen by BATSE and OSSE
  - J. Ellis *et al.*, A&A 402 (2003) 409
  - $E_{QG} > 6 \times 10^{15}$ GeV
- With 35 GRBs with known z seen by BATSE, HETE-2 and SWIFT
  - J. Ellis *et al.*, Astropart. Phys. 25 (2006) 402
  - $E_{QG} > 9 \times 10^{15}$ GeV
- With 17 GRBs including 11 with known z seen by INTEGRAL
  - R. Lamon et al., arXiv:0706.4039
  - $E_{QG} > 1.5 \times 10^{14}$ GeV, introducing a correction for intrinsic lags
- **With 15 GRBS with known z seen by HETE2**

J. Bolmont et al., astro-ph/0603725

$E_{QG} > 2.0 \times 10^{15}$ GeV **ApJ 676, 532 (2008)**

Other sources

- Any transient source can be used...
- Crab pulsar seen by EGRET
  - P. Kaaret, A&A 345 (1999) L32-L34
  - $E_{QG} > 1.8 \times 10^{15}$ GeV
- Flare of Mkn 421 seen by the Whipple Observatory
  - S.D. Biller et al., Phys. Rev. Lett. 83 (1999) 2108
  - $E_{QG} > 6 \times 10^{16}$ GeV
- Flare of Mkn 501 seen by MAGIC
  - J. Albert et al., arXiv:0708.2889
  - $E_{QG} > 2.6 \times 10^{17}$ GeV

- Flare of PKS2155-304 observed by H.E.S.S.
  $\rightarrow$ this presentation